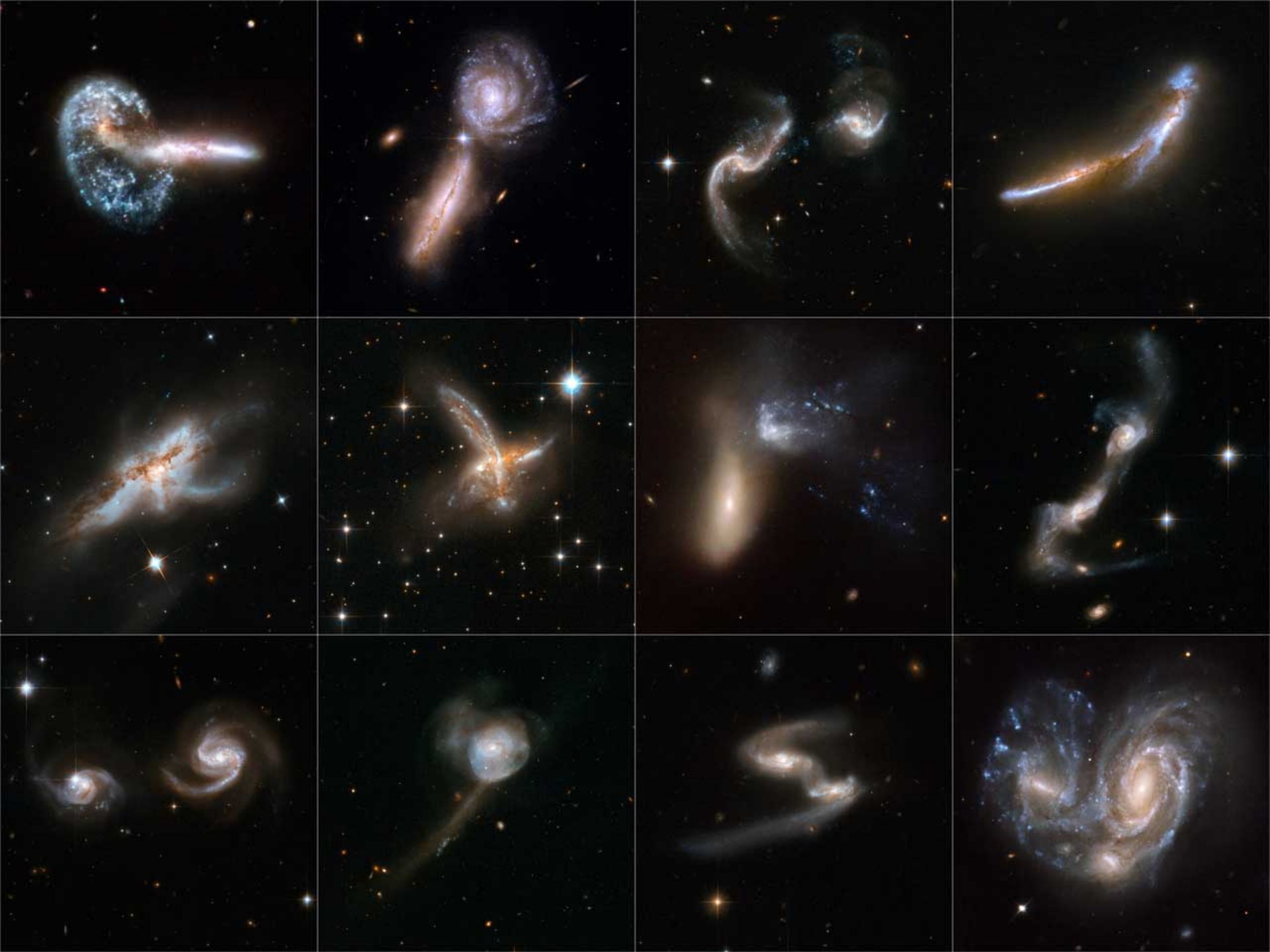
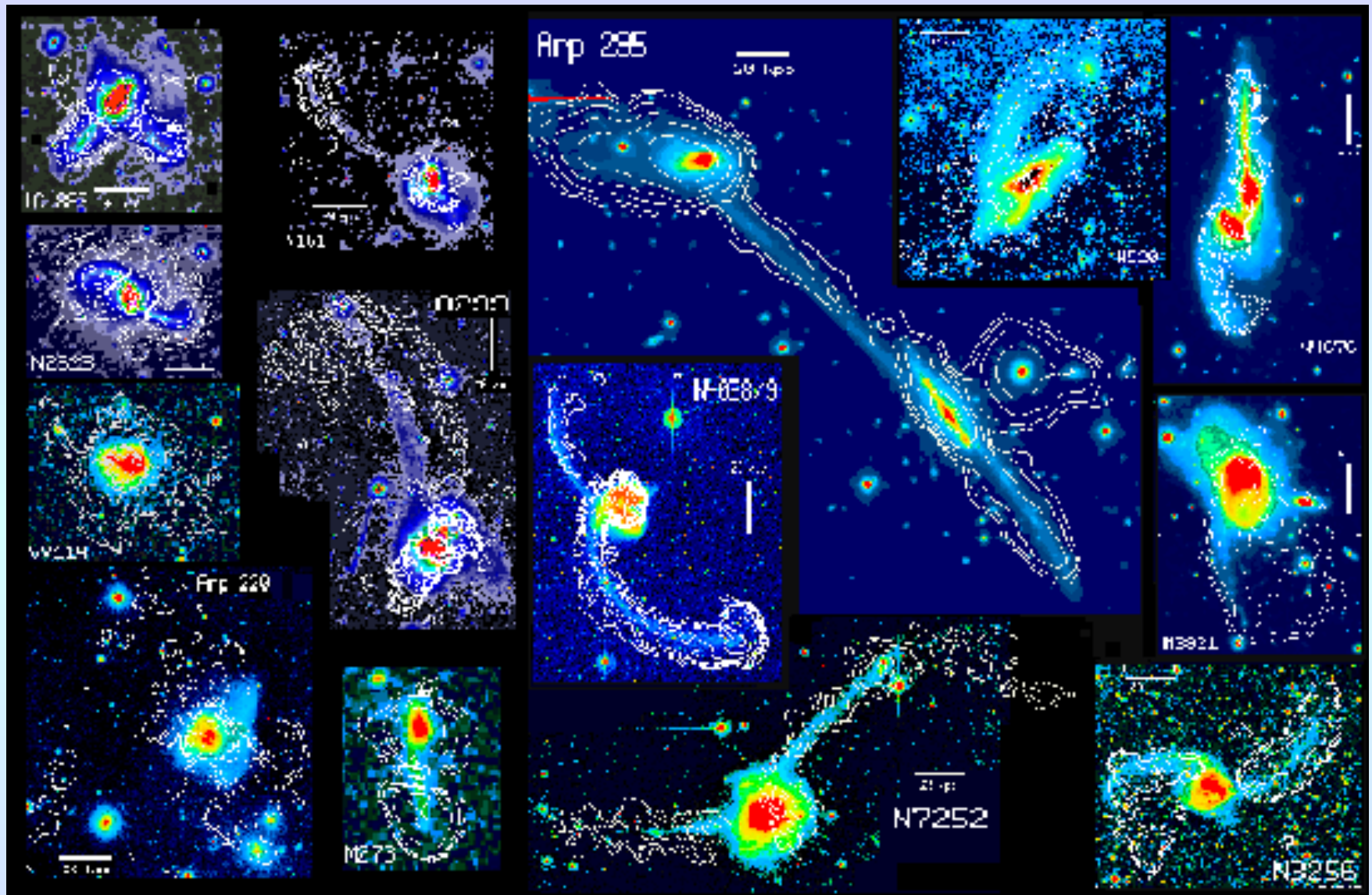


# Peculiar (Interacting) Galaxies

Not all galaxies fall on the Hubble sequence: many are peculiar! In 1966, Arp created an Atlas of Peculiar Galaxies based on pictures from the Palomar Sky Survey. In 1982, he extended the catalog to the southern hemisphere (based on the newly commissioned UK Schmidt in Australia). He identified

- Grossly distorted morphologies
- Tidal tails
- Polar rings around ellipticals
- Ring-shaped galaxies
- Rings of dust and/or gas
- Warps in spiral disks
- Shells and ripples around ellipticals
- Accretion of dwarf galaxies





Montage of peculiar galaxies from John Hibbard, with HI contours over false color optical images



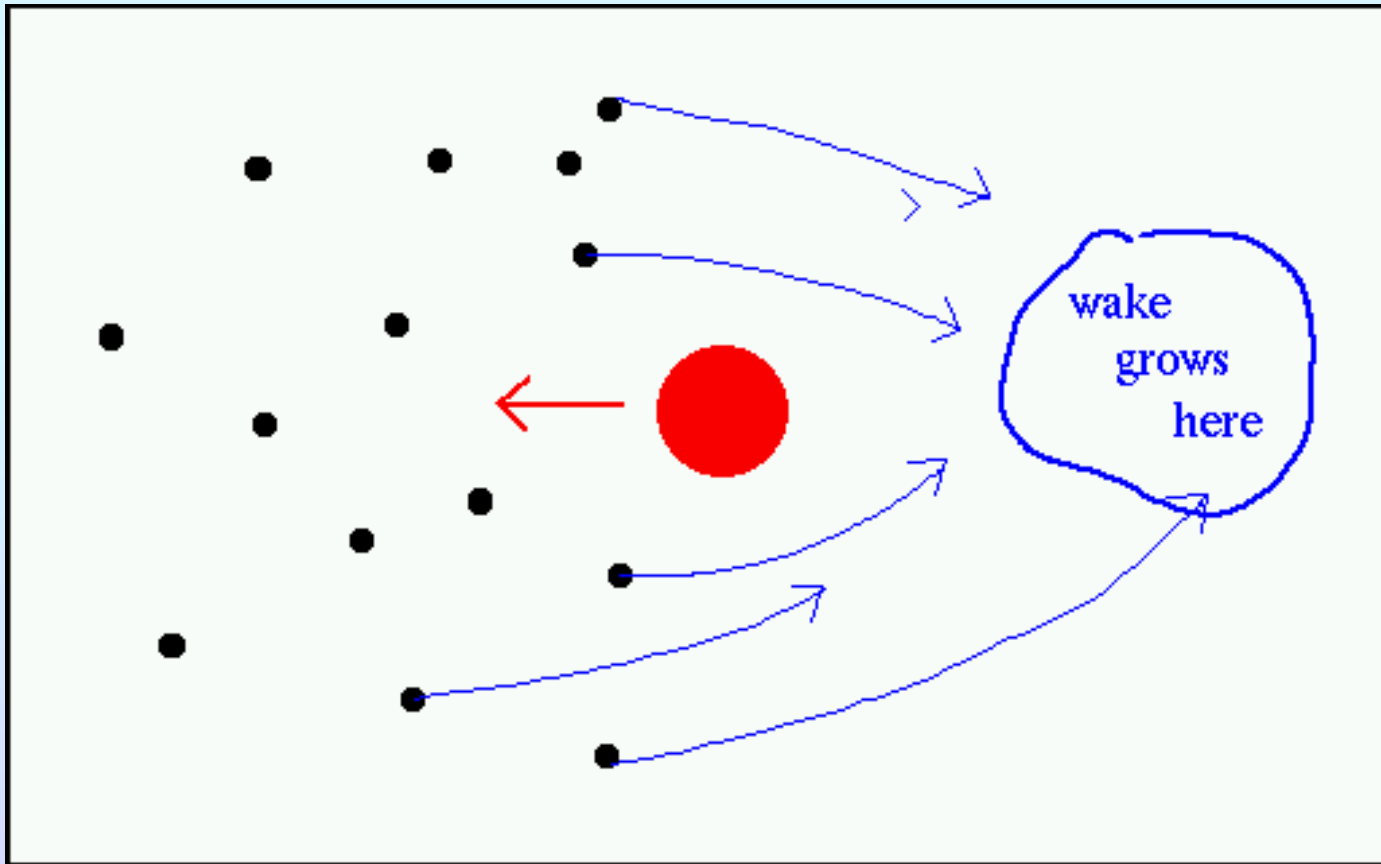
# Galaxy Groups and Interactions

- Galaxies are social creatures, and are almost always found in pairs, groups, and clusters
- Galaxy groups have less than  $\sim 50$  galaxies, sizes of  $\sim 1$ -2 Mpc, velocity dispersions of  $\sigma \sim 100$  to 500 km/s
- In contrast, galaxy clusters have several thousands of galaxies, sizes  $\sim$  few Mpc,  $\sigma \sim 700$  to 1200 km/s

Either way, the typical distances between galaxies can lead to interactions. Galaxy collisions are not uncommon!

# Dynamical Friction

As a massive galaxy moves through a “sea” of stars, gas, (and the dark halo), it causes a wake behind it, increasing the mass density behind it. This causes the galaxy to lose kinetic energy, and merge with its companion.



# Dynamical Friction

The exact force associated with dynamical friction can be derived from relaxation time considerations. But to a good approximation, it is

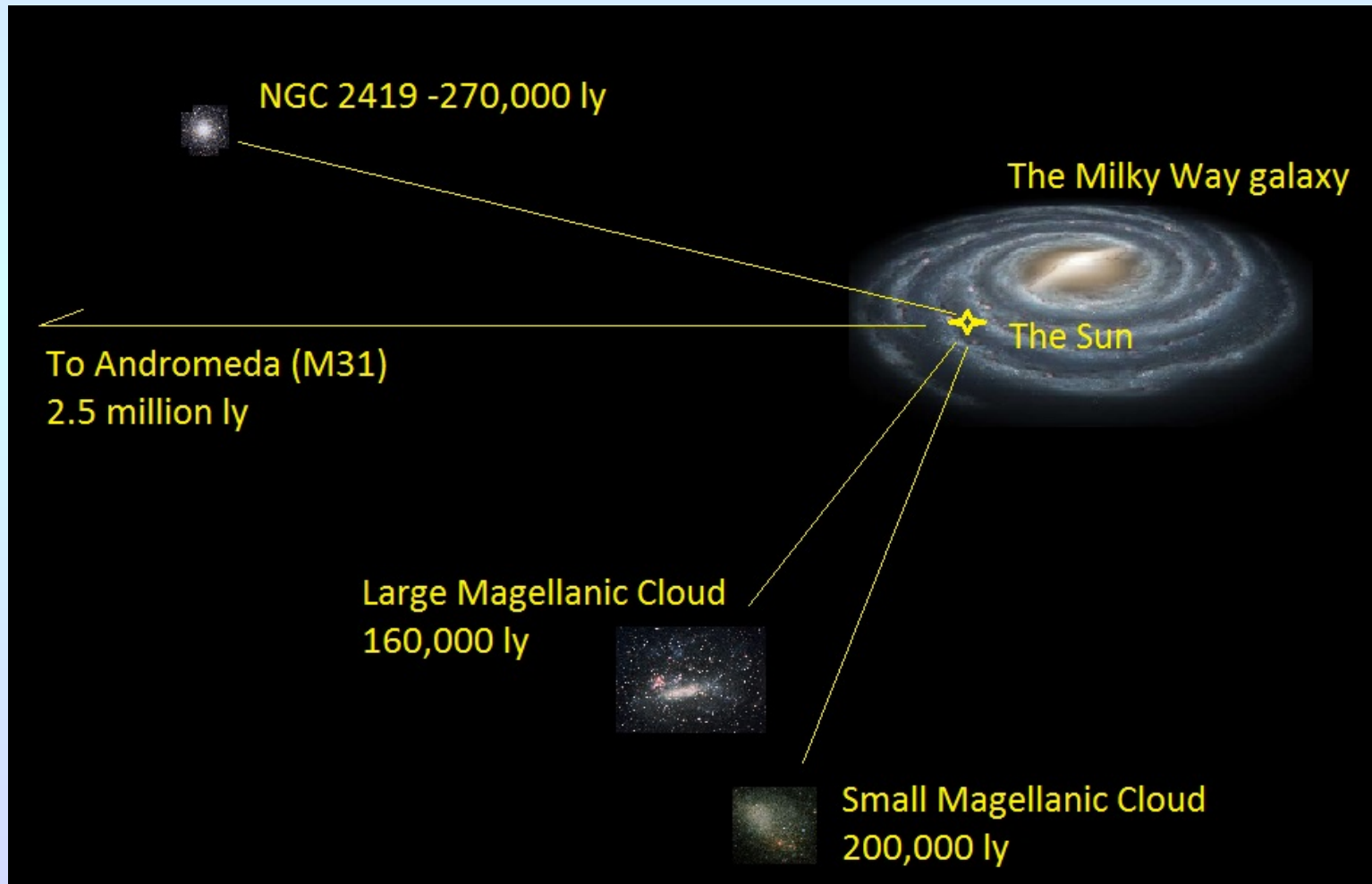
$$F_{dyn} = C \left[ \frac{G^2 M^2 \rho}{v_m^2} \right]$$

where  $M$  and  $v_m$  are the mass and velocity of the infalling galaxy,  $\rho$  is the density of stars encountered, and  $C$  depends on how  $v_m$  compares the star's velocity dispersion. Note:

- The slower the galaxy's speed, the stronger the dynamical force, the more intense the interaction
- The more massive the object, the greater the effect

# Example: the Milky Way and the LMC

The Large Magellanic Cloud is  $\sim 50$  kpc from the Milky Way.  
How long until the galaxies merge?



# Example: the Milky Way and the LMC

The Large Magellanic Cloud is  $\sim 50$  kpc from the Milky Way.  
How long until the galaxies merge?

For a dark matter halo that produces a flat rotation curve,

$$\rho(r) = \frac{v^2}{4\pi G r^2}$$

then

$$F_{dyn} = \frac{C G^2 M^2 \rho}{v^2} \Rightarrow \frac{C G M^2}{4\pi r^2}$$

Now consider the torque on the galaxy, i.e., the change in the LMC's angular momentum

$$\tau = \frac{dL}{dt} = r \times F_{dyn} = M v \frac{dr}{dt} \quad (\text{for a circular orbit})$$

# Example: the Milky Way and the LMC

So

$$\frac{dL}{dt} = r \times F_{dyn} = M v \frac{dr}{dt} = -r \times \frac{CGM^2}{4\pi r^2} \sim \frac{CGM^2}{4\pi r}$$

Integrating both sides gives

$$r dr = -\frac{CGM}{4\pi v} dt \Rightarrow \int_R^0 r dr = -\frac{CGM}{4\pi v} \int_0^t dt$$

For a merger time

$$t = \frac{2\pi v R^2}{CGM}$$

# Example: the Milky Way and the LMC

For the LMC,  $M = 2 \times 10^{10} M_{\odot}$ ,  $v = 220$  km/s,  $R = 50$  kpc, and  $C = 23$ . So

$$t = \frac{2\pi v R^2}{CGM} \sim 1.7 \text{ Gyr}$$

Actually if we assume an elongated orbit, the answer is a much longer merger time ( $\sim 5$  Gyr). This is still short compared to a Hubble time, but it is long enough so that we should be able to find systems in the act of merging.

# Effects of a Galaxy Interaction

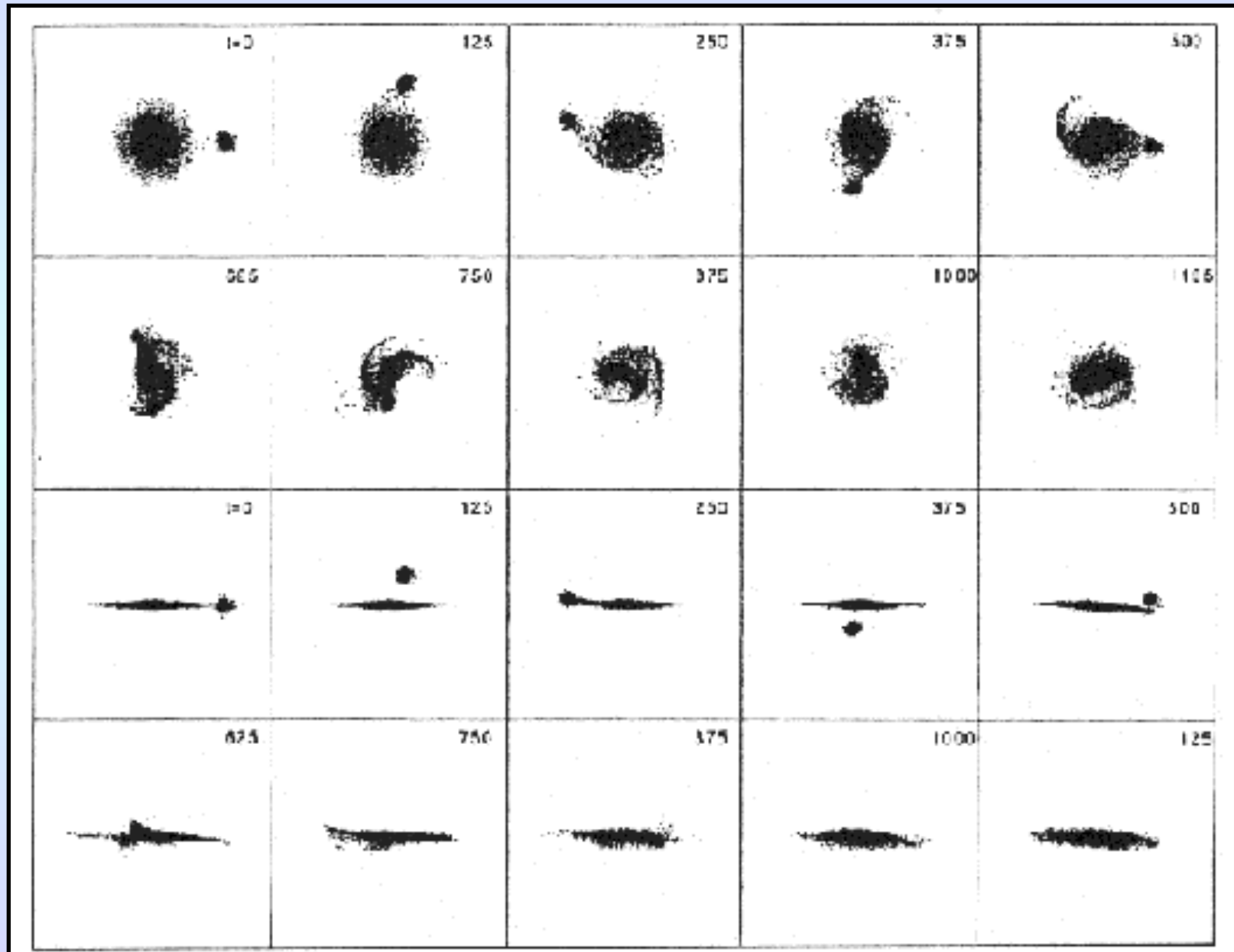
- When two galaxies interact, the energy sapped from their motion via dynamical friction is transferred to the random motions of the stars. If, before the interaction a galaxy had a total energy  $E_0$ , and by the Virial Theorem,

$$2KE_0 + PE_0 = 0 \Rightarrow KE_0 + PE_0 = -KE_0$$

Dynamical friction increases the kinetic energy in random stellar motions by  $\Delta KE$  !

- Since total energy is conserved, well after the encounter, when system is again virialized,  $KE_1 = -E_1 = -(E_0 + \Delta KE) = KE_0 - \Delta KE$
- Stars that acquire the most KE escape; the rest remain loosely attached, “puffing up” the system

# Minor merger (Walker et al. 1996)

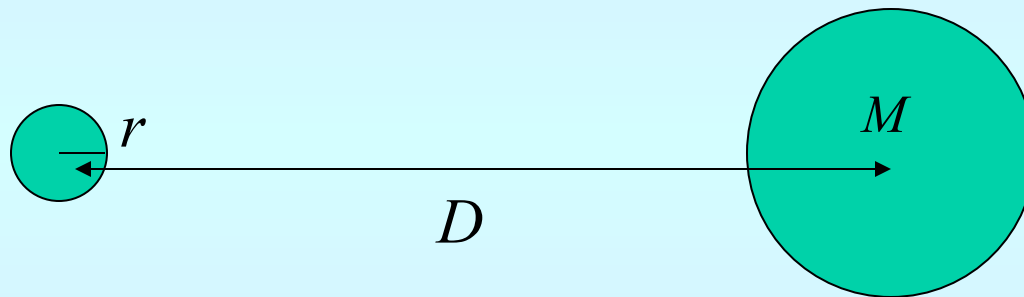


# Tidal Stripping

Consider a small galaxy of mass  $m$  and radius  $r$  orbiting a larger galaxy of mass  $M$  at a distance  $D$ . The stars on one side of the satellite galaxy feel an acceleration that is different from the stars on the other side of the galaxy. This sets up a tidal force and energy is no longer conserved!

# Tidal Stripping

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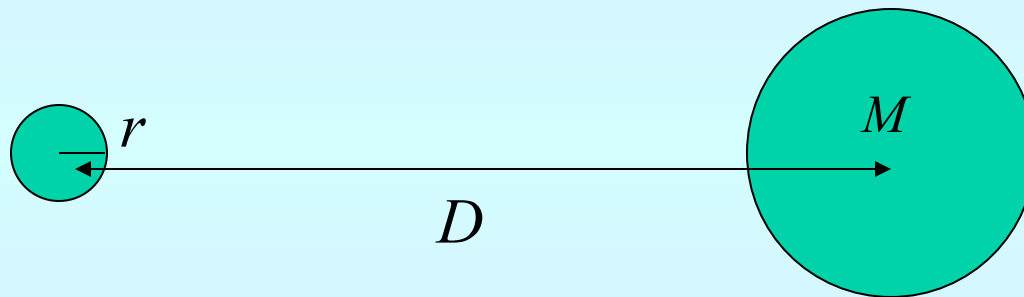
The differential acceleration on satellite is

$$\Delta a = \frac{GM}{D^2} - \frac{GM}{(r+D)^2}$$

If  $r \ll D$ , then  $\Delta a = \frac{2GMr}{D^3}$

# Tidal Stripping

Consider a small galaxy of mass  $m$  and radius  $r$  orbiting a larger galaxy of mass  $M$  at a distance  $D$ . The stars on one side of the satellite galaxy feel an acceleration that is different from the stars on the other side of the galaxy. This sets up a tidal force and energy is no longer conserved!



When  $\Delta a >$  gravitational binding acceleration, stars will be stripped

$$\Delta a = \frac{2GMr}{D^3} > \frac{Gm}{r^2} \quad \text{or} \quad r > r_J = D \left\{ \frac{m}{2M} \right\}^{1/3}$$

where  $r_J$  is the Jacobi radius (or Roche limit)

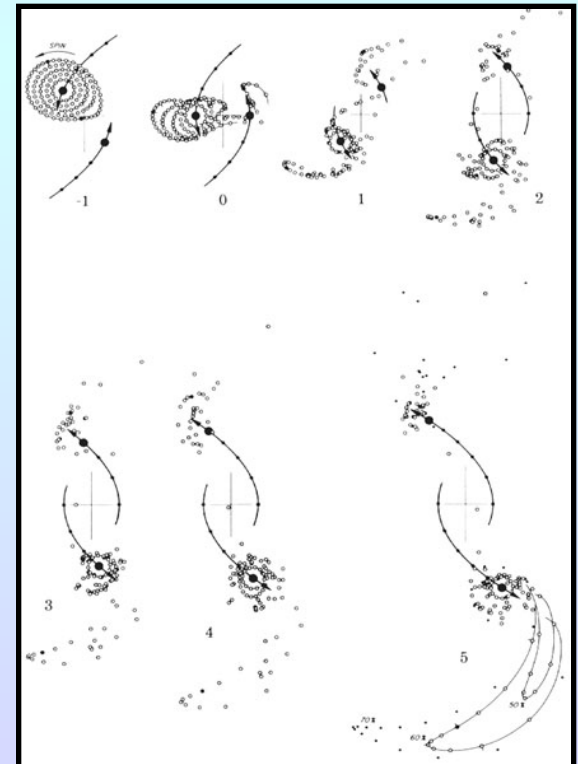
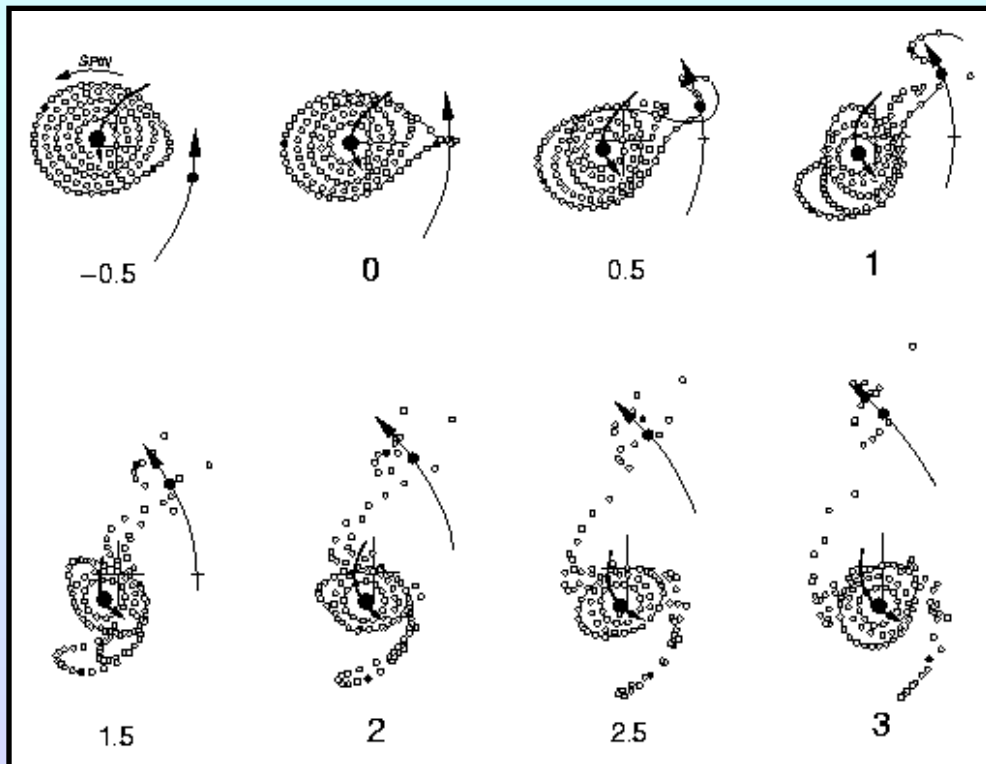
# Galaxy Interactions

Some terminology:

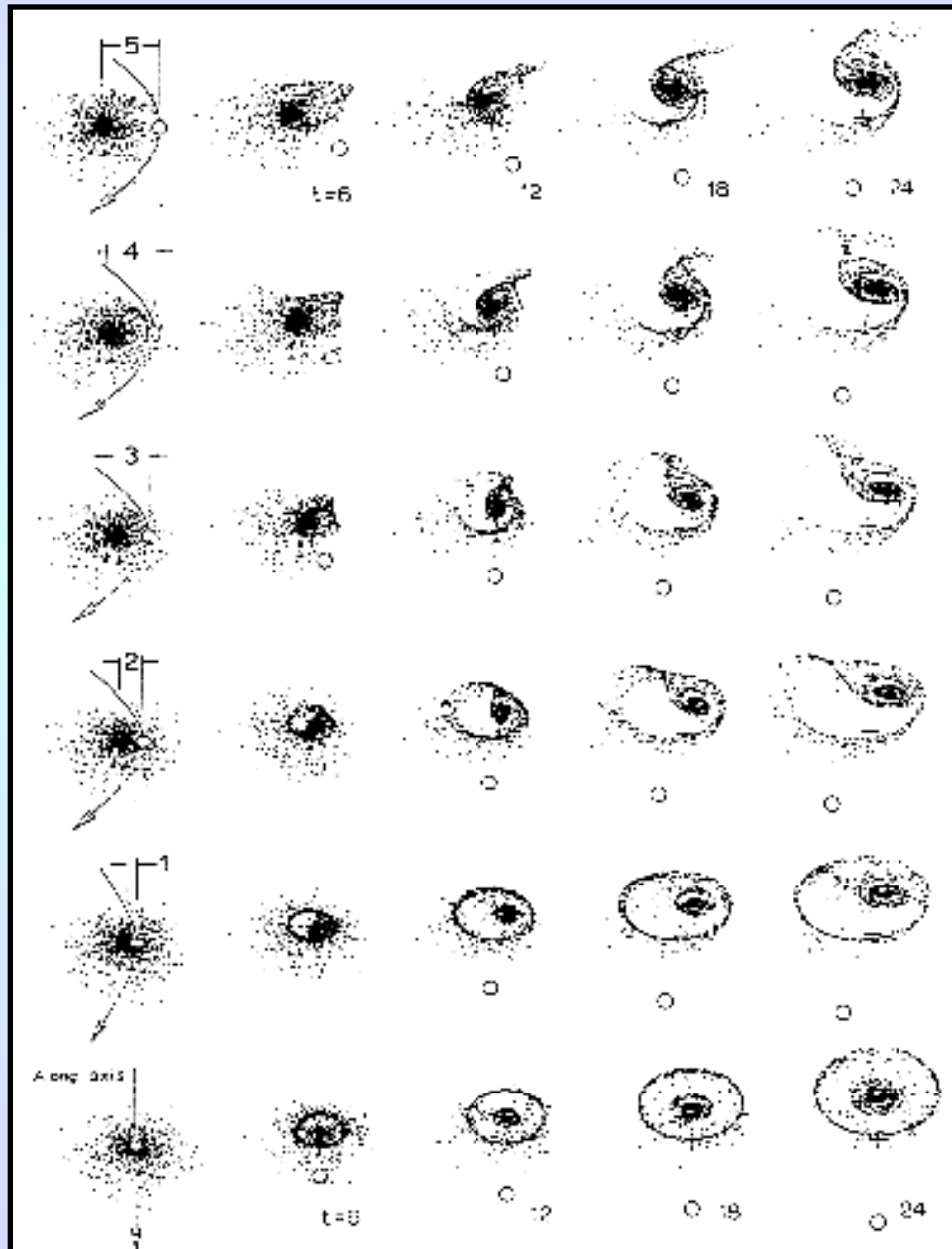
- Major mergers: Two similar mass galaxies. This gives rise to tidal tails.
- Minor mergers: A satellite (dwarf?) galaxy merges with a massive galaxy. This makes bridges, also produces tidal stripping
- Retrograde/Direct: The main galaxy is rotating in the opposite/same direction to the “intruder”
- Impact radius: The distance between center of galaxy and the intruder galaxy
- Inclination angle: The angle between the main galaxy’s galactic and the intruder
- Viewing angle: our line of sight to the merger
- Dry Merger: Merger of galaxies with little or no gas
- Wet Merger: Merger of galaxies with gas; the collision of the gas clouds causes star formation and supernovae, which then affect the gas. (This is called feedback.)

# Galaxy Interactions

Galaxy interactions are studied numerically via N-body simulations, which include the effects of gas, star formation, and dark halo mass. The seminal paper for this was Toomre & Toomre (1972), who were able to reproduce many of the observed features of interacting galaxies with very simple simulations (only a few 100 particles, no gas, no dark matter).



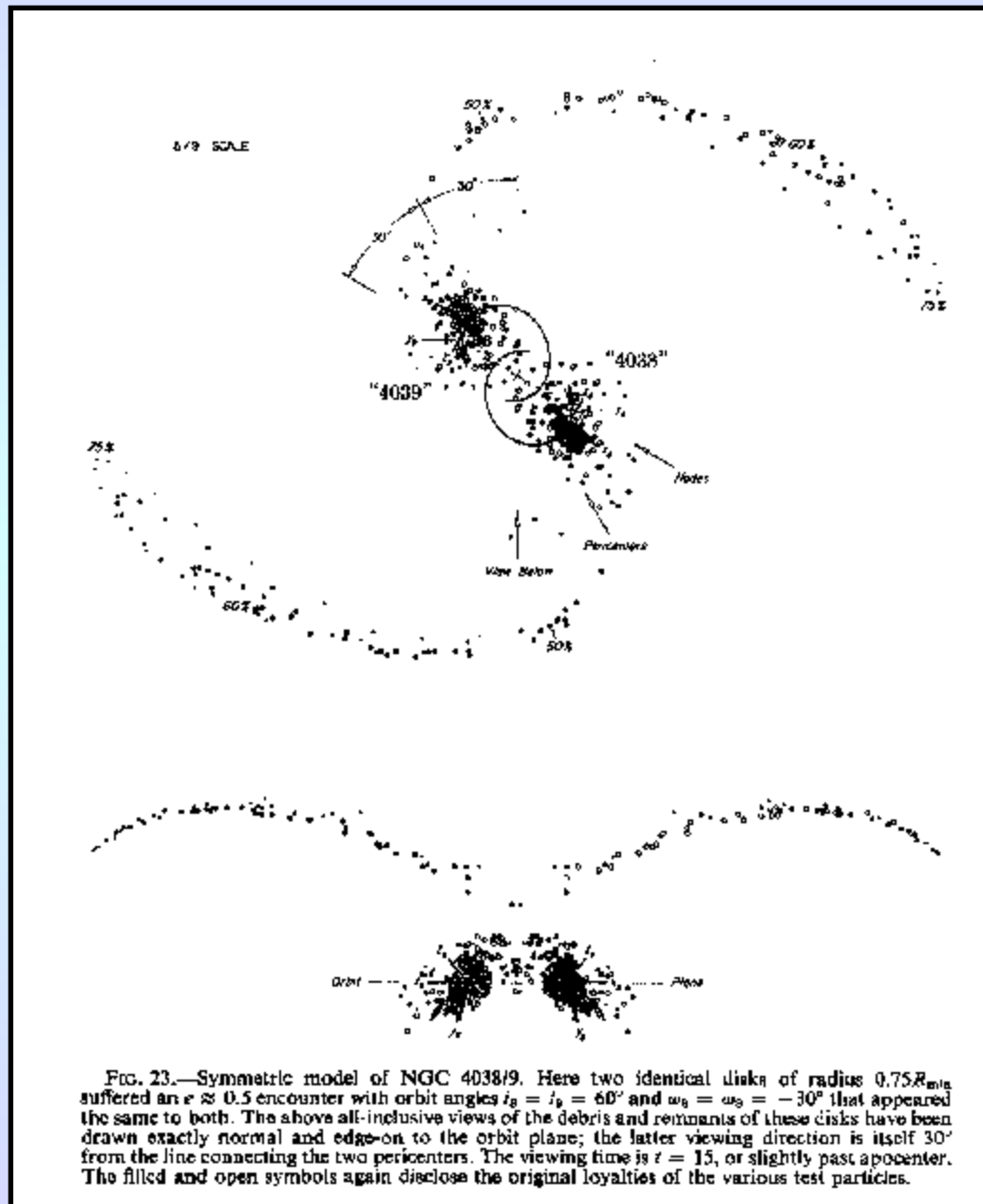
# Effect of Impact Radius Toomre (1978)



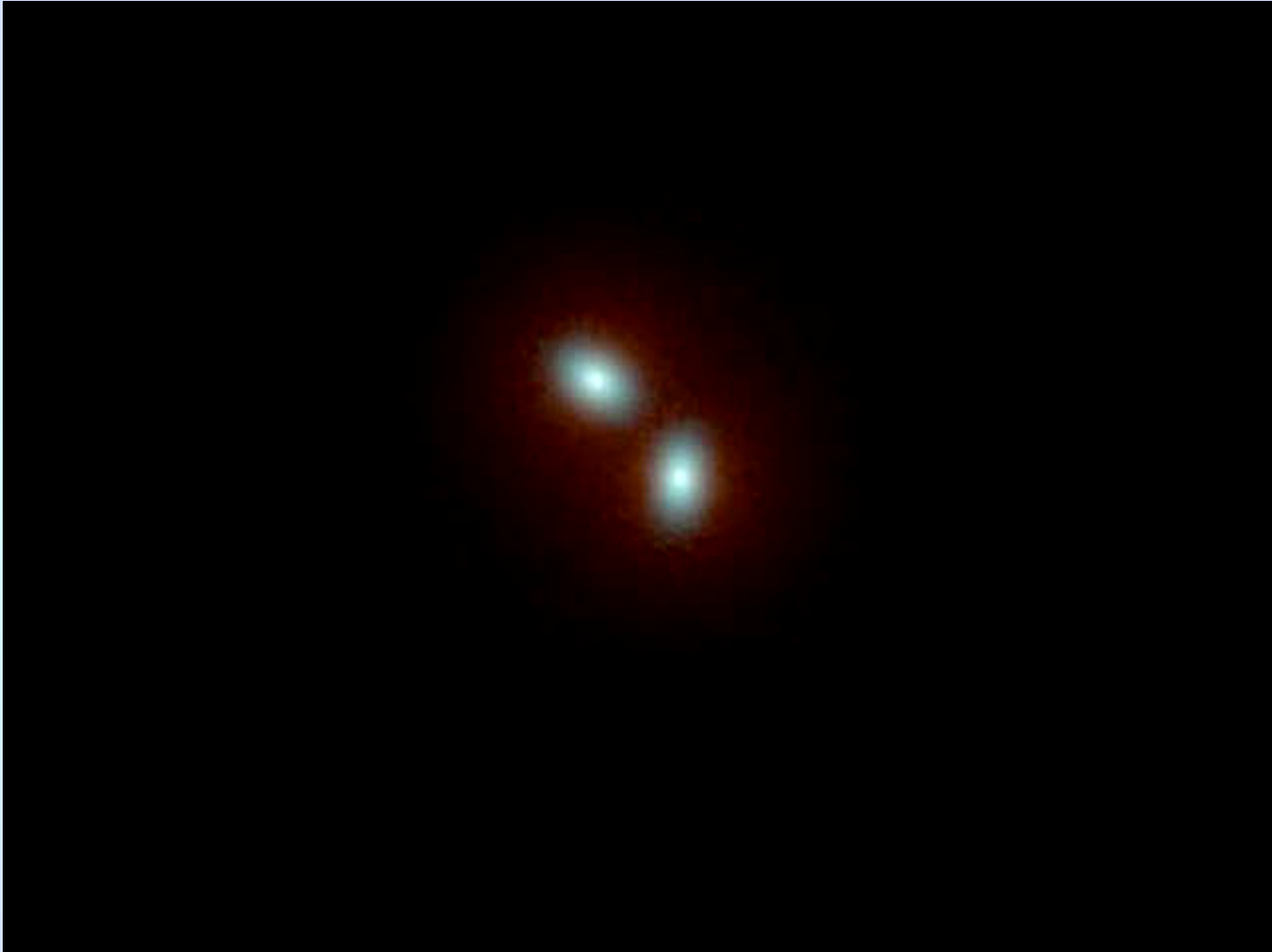
# Example: The Antennae Galaxy



# Toomre & Toomre (1972): The Antennae

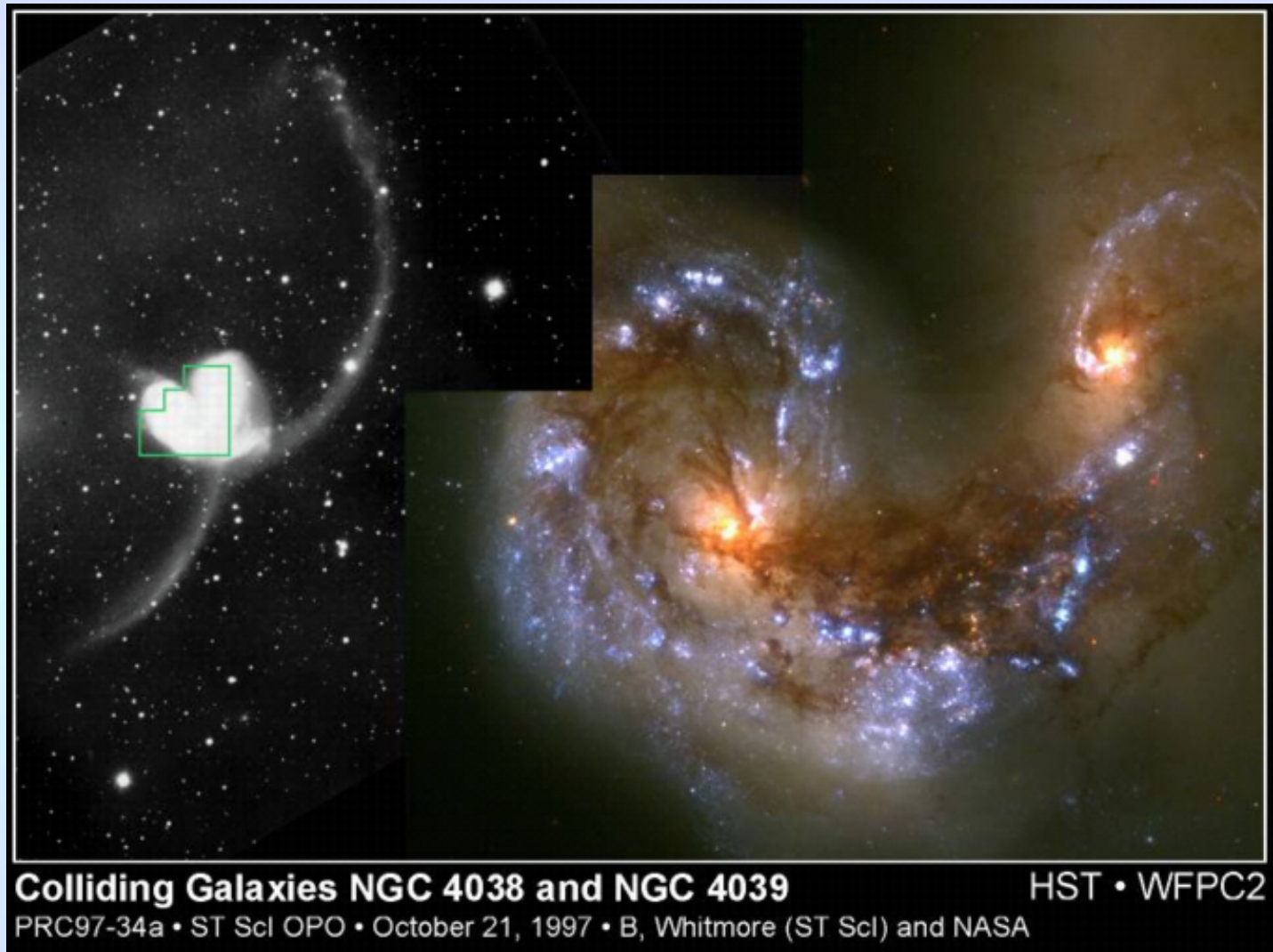


# Example: The Antennae Galaxy



(White/blue is stars and gas; red is dark matter)

# Example: The Antennae Galaxy

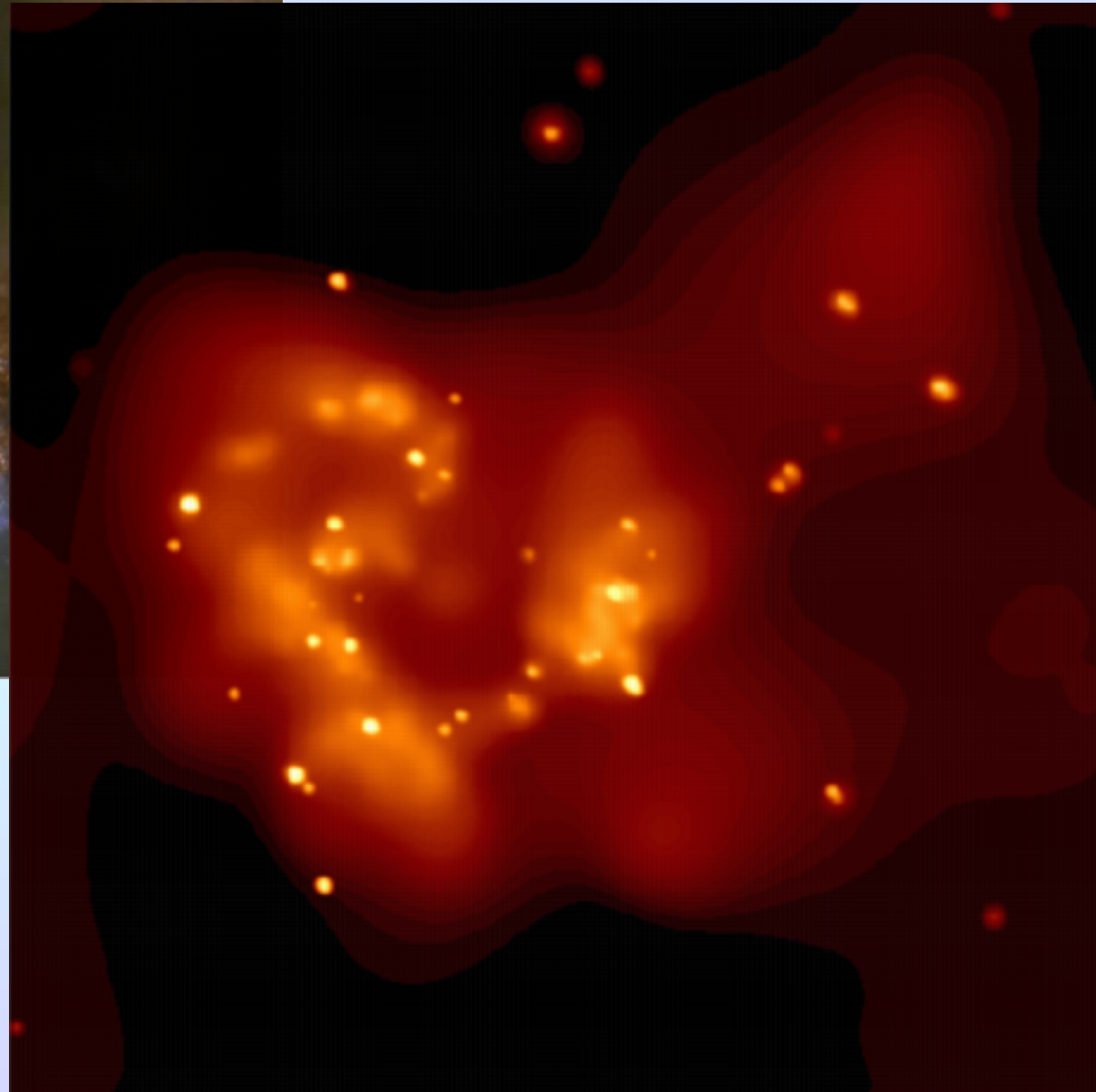


In the center of the system, large numbers of bright star clusters are being created

# The Central Antennae



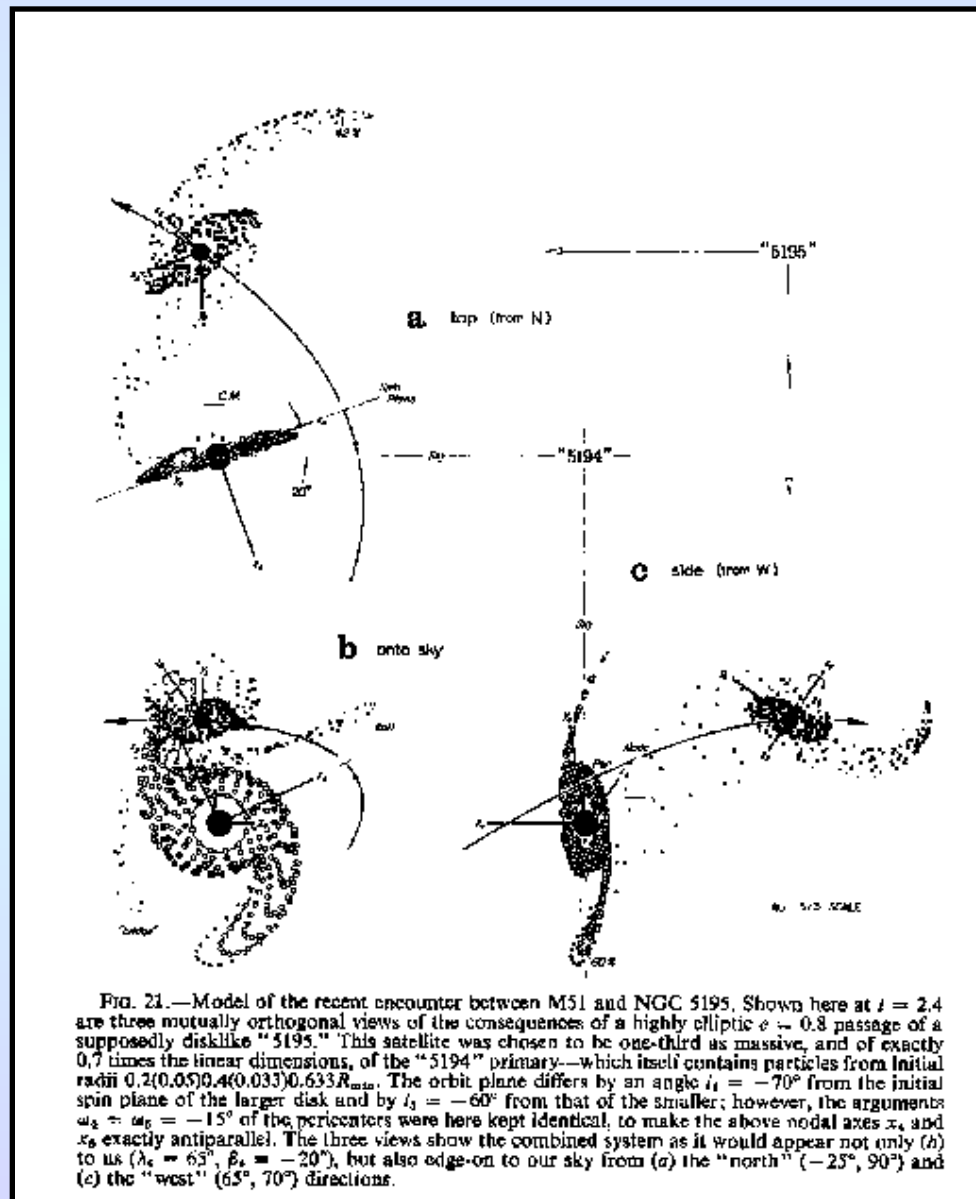
X-ray





M51 – the Whirlpool

# Model of M51 Interaction (Toomre & Toomre 1972)



# Whirlpool Galaxy • M51



NASA and The Hubble Heritage Team (STScI/AURA)  
Hubble Space Telescope WFPC2 • STScI-PRC01-10

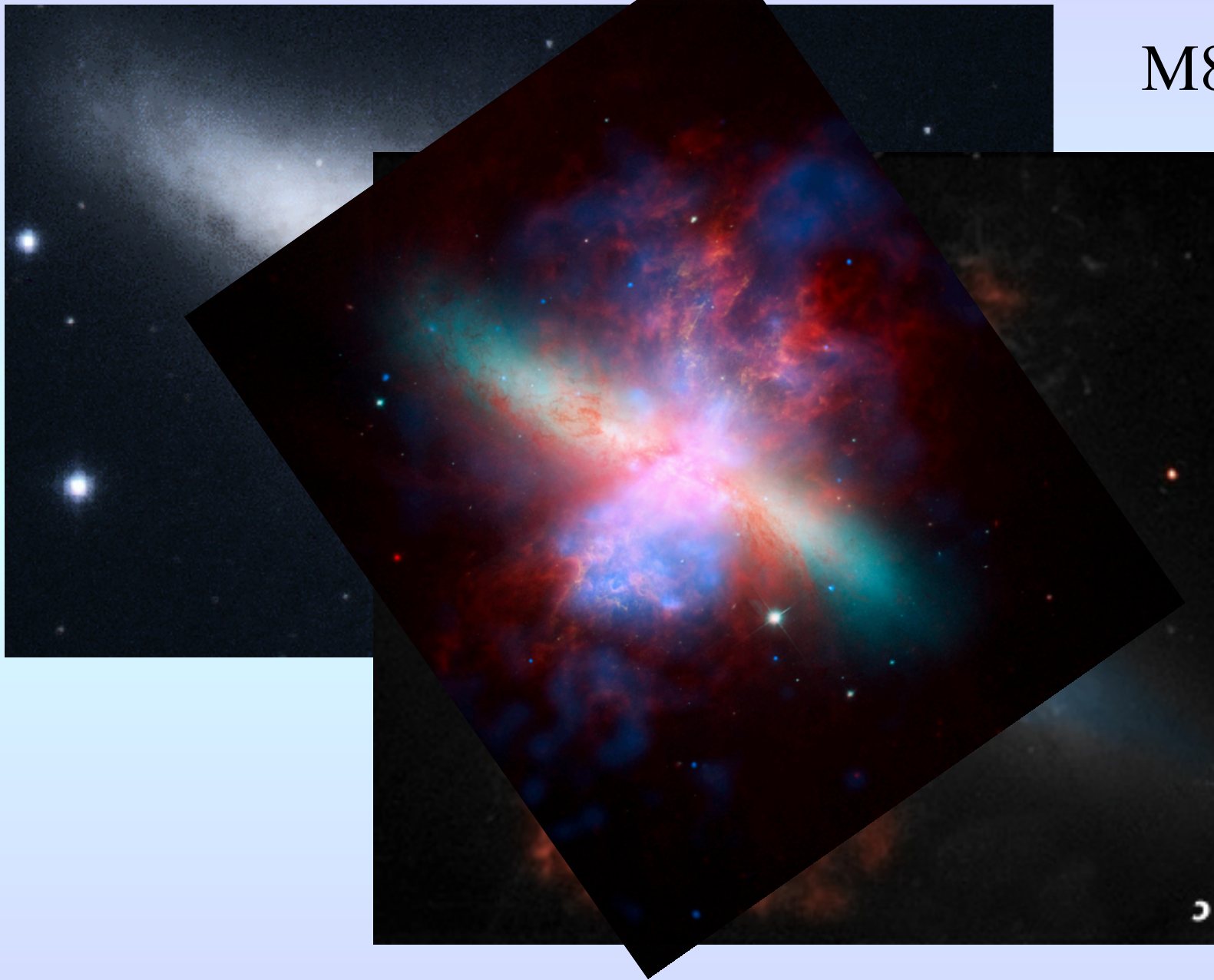
Hubble  
Heritage

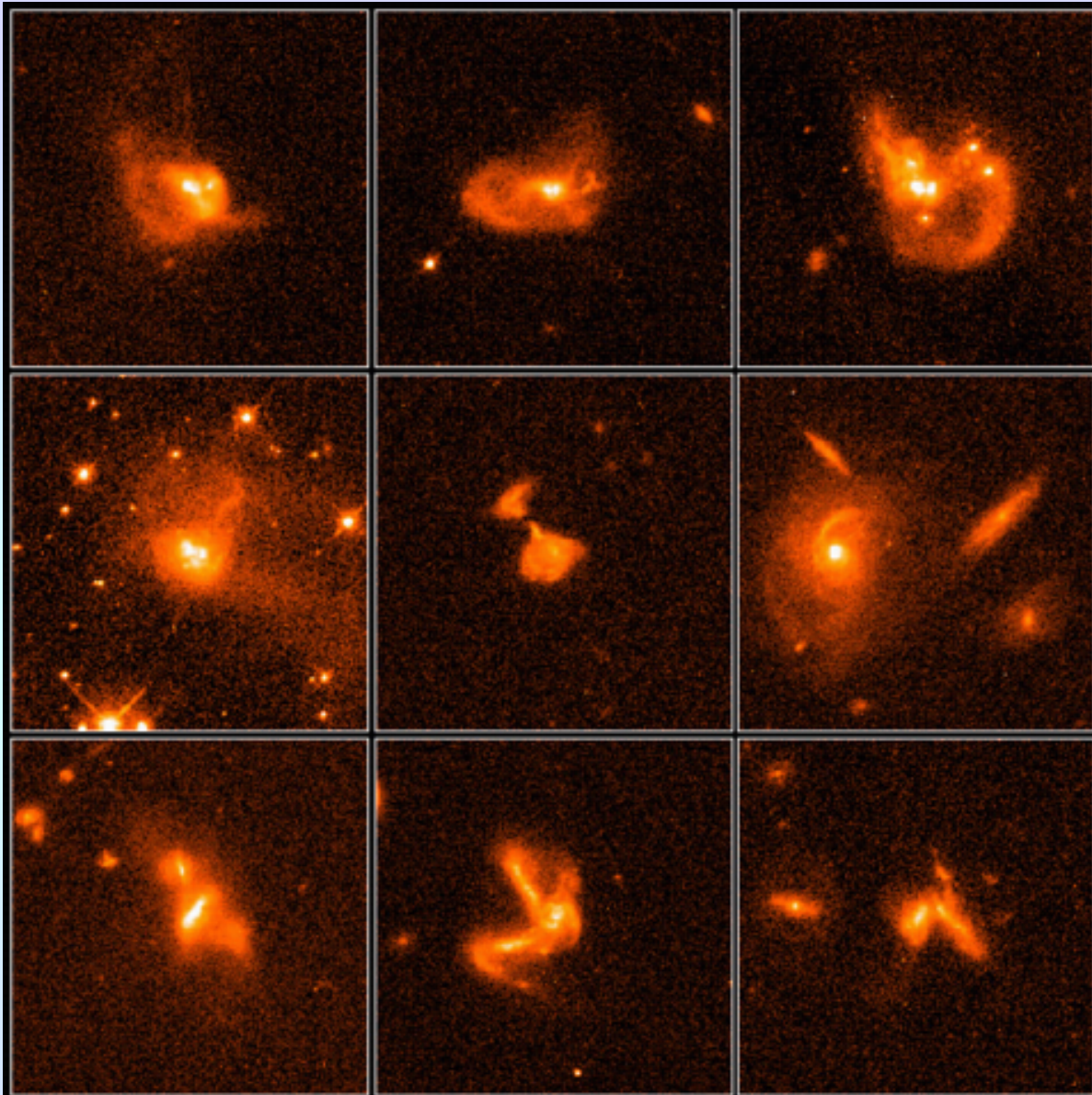
# Starburst Activity

Both direct mergers and indirect interactions can trigger star formation, due to collisions between gas clouds. In addition

- Gas which loses enough angular momentum during the encounter will fall into the center. (This is especially true if a bar is formed.) This can lead to *strong* nuclear starbursts.
  - M82 is currently forming a few  $M_{\odot}$ /year of stars (similar to a large spiral) in a nuclear area only 100 pc across!
- Powerful starbursts surrounded by dust will be very bright in the infrared
- The highest star formation rates are associated with ultraluminous infrared galaxies (ULIRGs), which were first discovered by the IRAS satellite. These have  $L > 10^{12} L_{\odot}$ , but almost all their light comes out in the infrared. These galaxies are merging too!

M82





## **Ultraluminous Infrared Galaxies**      **HST • WFPC2**

NASA and K. Borne (Raytheon ITSS and NASA Goddard Space Flight Center), H. Bushouse (STScI), L. Colina (Instituto de Fisica de Cantabria, Spain) and R. Lucas (STScI)

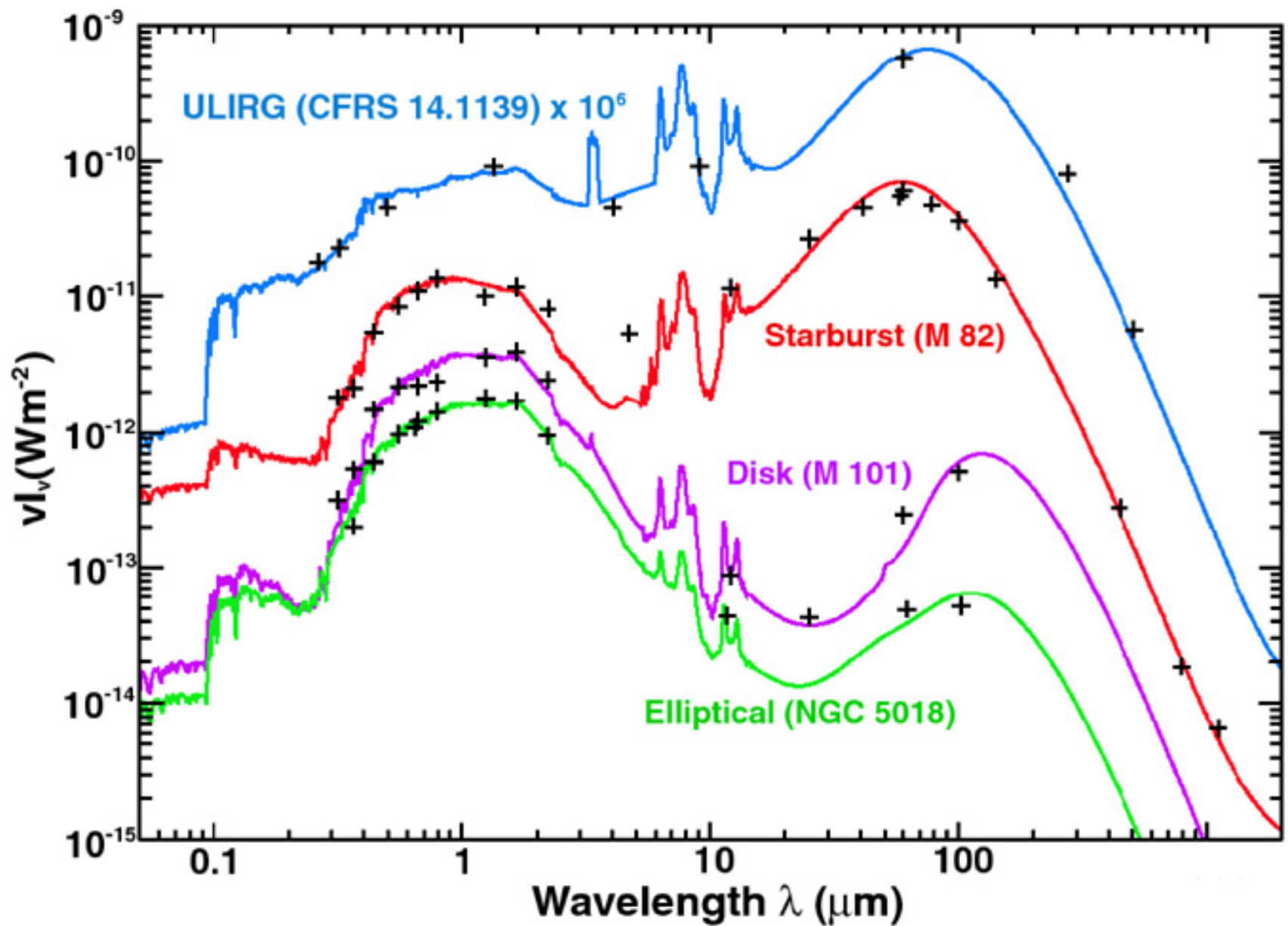


Fig 7.7 (P. Chaniai, G. Lagache) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



**Interacting Galaxies NGC 1409 and NGC 1410**

NASA and W. Keel (University of Alabama) • STScI-PRC01-02

**HST • WFPC2**

## Galaxies NGC 2207 and IC 2163



Hubble  
Heritage

NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC99-41

## Interacting Galaxy System NGC 6745



Hubble  
Heritage

NASA and The Hubble Heritage Team (STScI/AURA)  
Hubble Space Telescope WFPC2 • STScI-PRC00-34

# The Tadpole





The Mice

# Toomre & Toomre (1972): The Mice

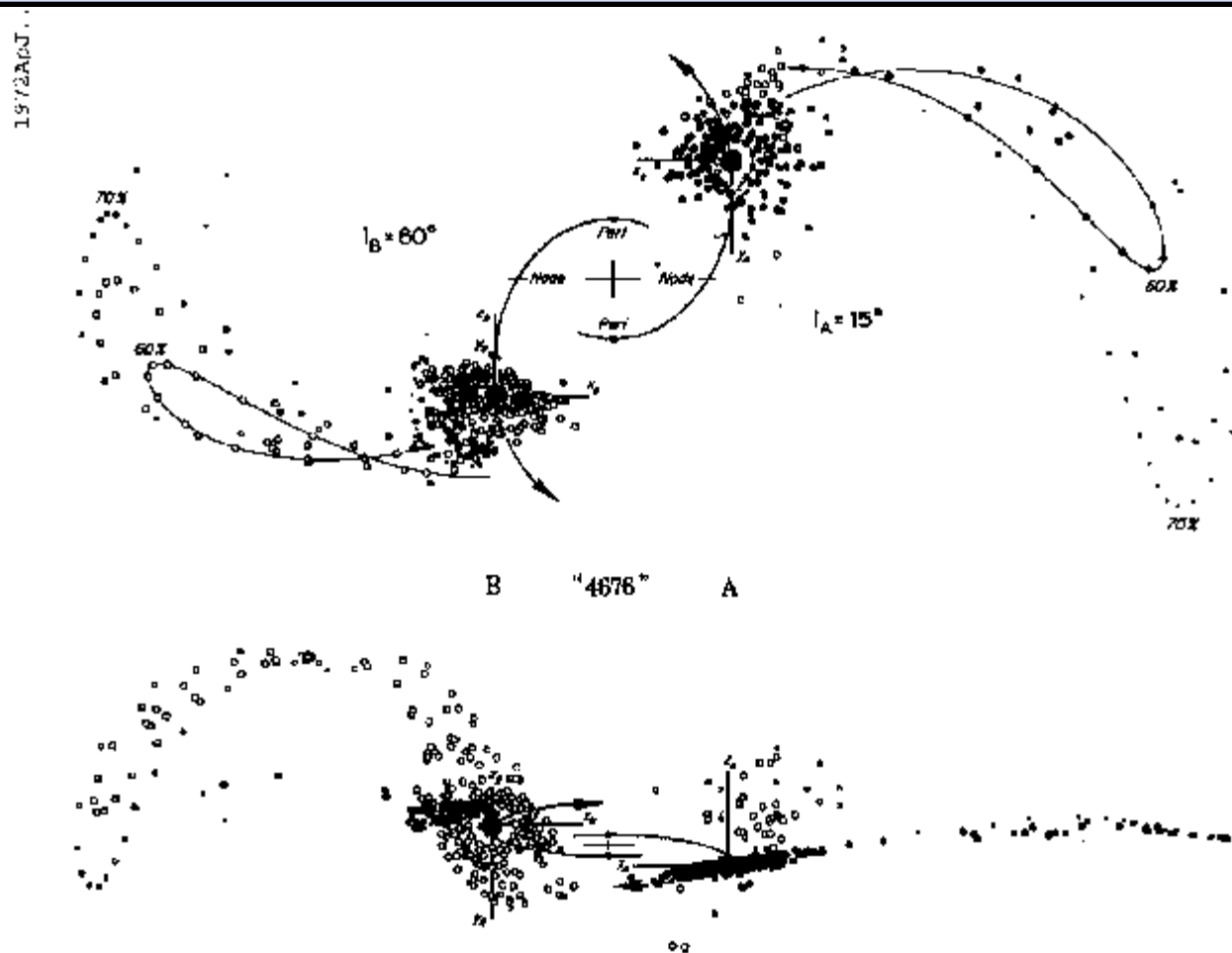
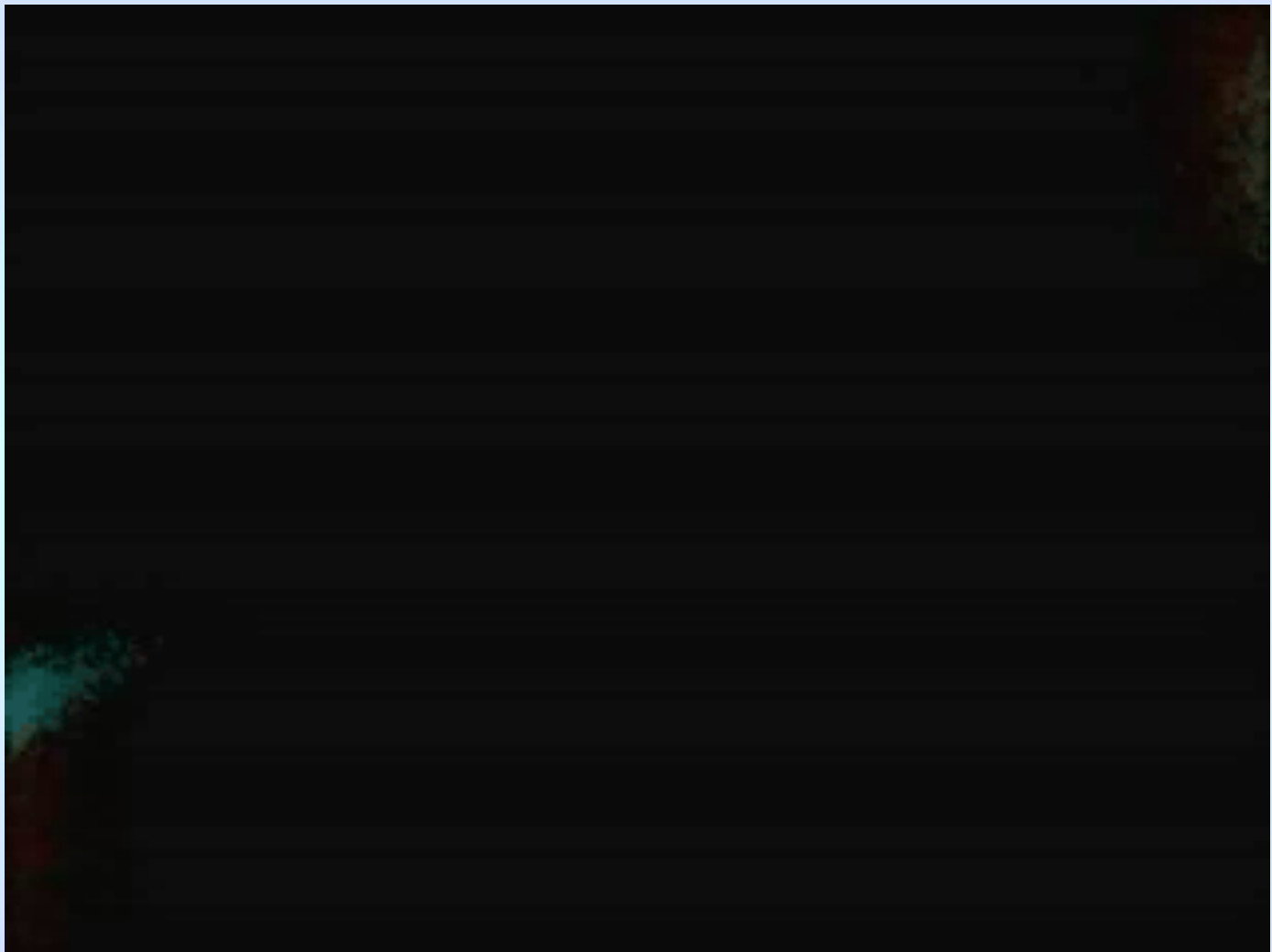
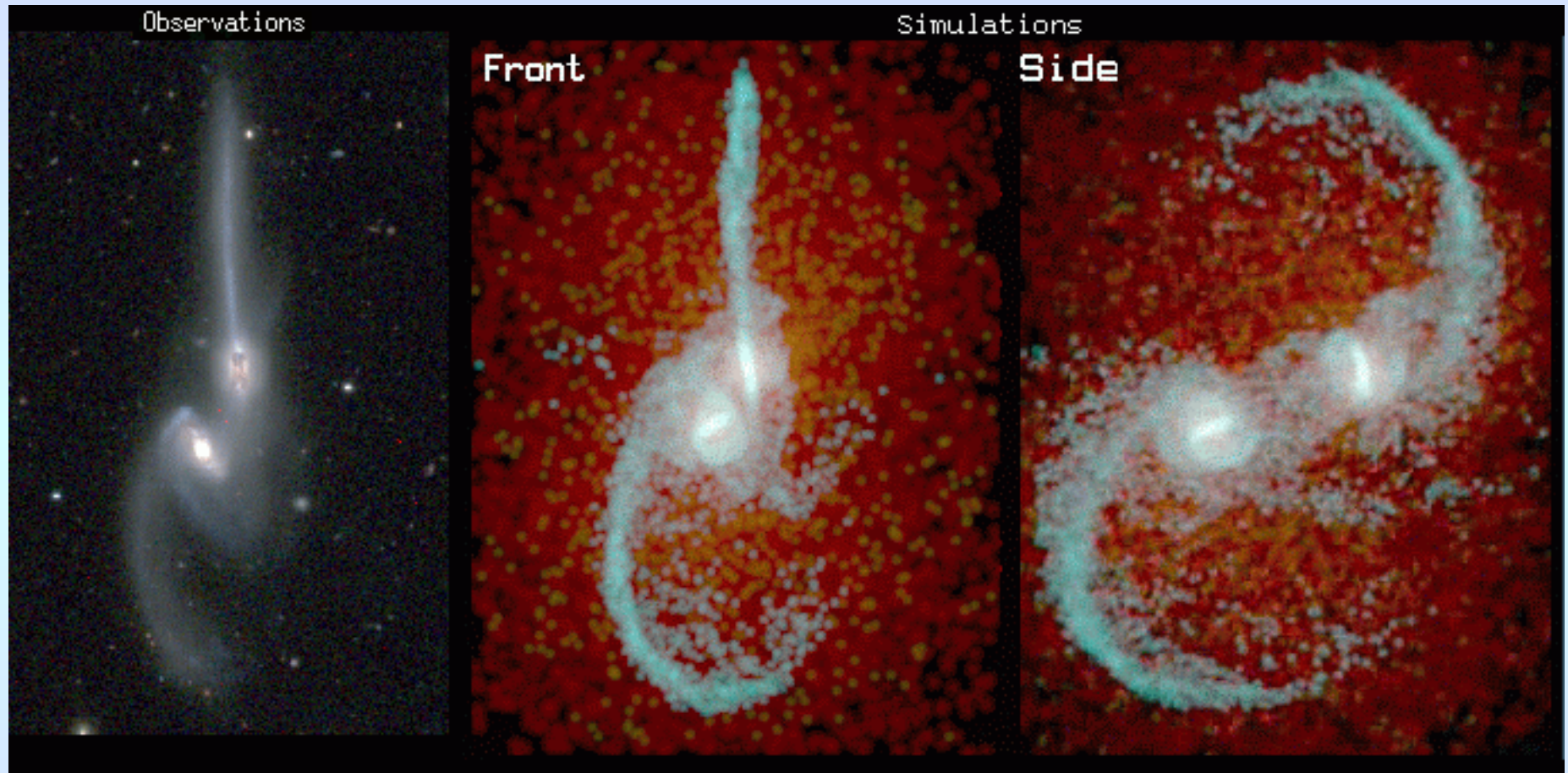


FIG. 22.—Model of NGC 4676. In this reconstruction, two equal disks of radius  $0.7R_{\text{gal}}$  experienced an  $e = 0.6$  elliptic encounter, having begun flat and circular at the time  $t = -16.4$  of the last apocenter. As viewed from either disk, the adopted node-to-peri angles  $\omega_A = \omega_B = -90^\circ$  were identical, but the inclinations differed considerably;  $i_A = 15^\circ$ ,  $i_B = 60^\circ$ . The resulting composite object at  $t = 6.086$  (cf. fig. 18) is shown projected onto the orbit plane in the upper diagram. It is viewed nearly edge-on to the same—from  $\lambda_A = 180^\circ$ ,  $\beta_A = 85^\circ$  or  $\lambda_B = 0^\circ$ ,  $\beta_B = 160^\circ$ —in the lower diagram meant to simulate our actual view of that pair of galaxies. The filled and open symbols distinguish particles originally from disks A and B, respectively.

# Simulation of the Mice



# Simulation of the Mice



# Simulation of the Mice

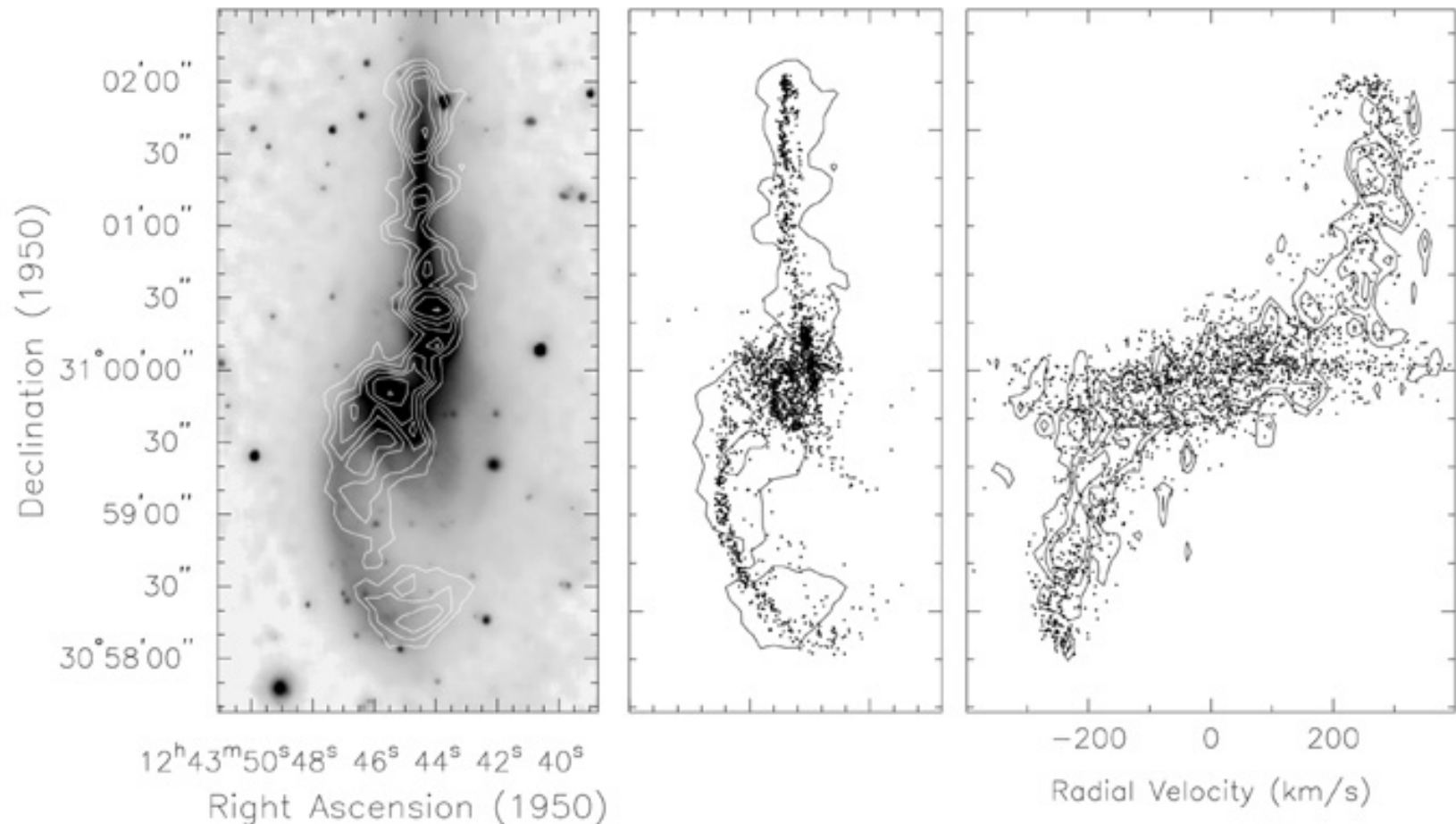
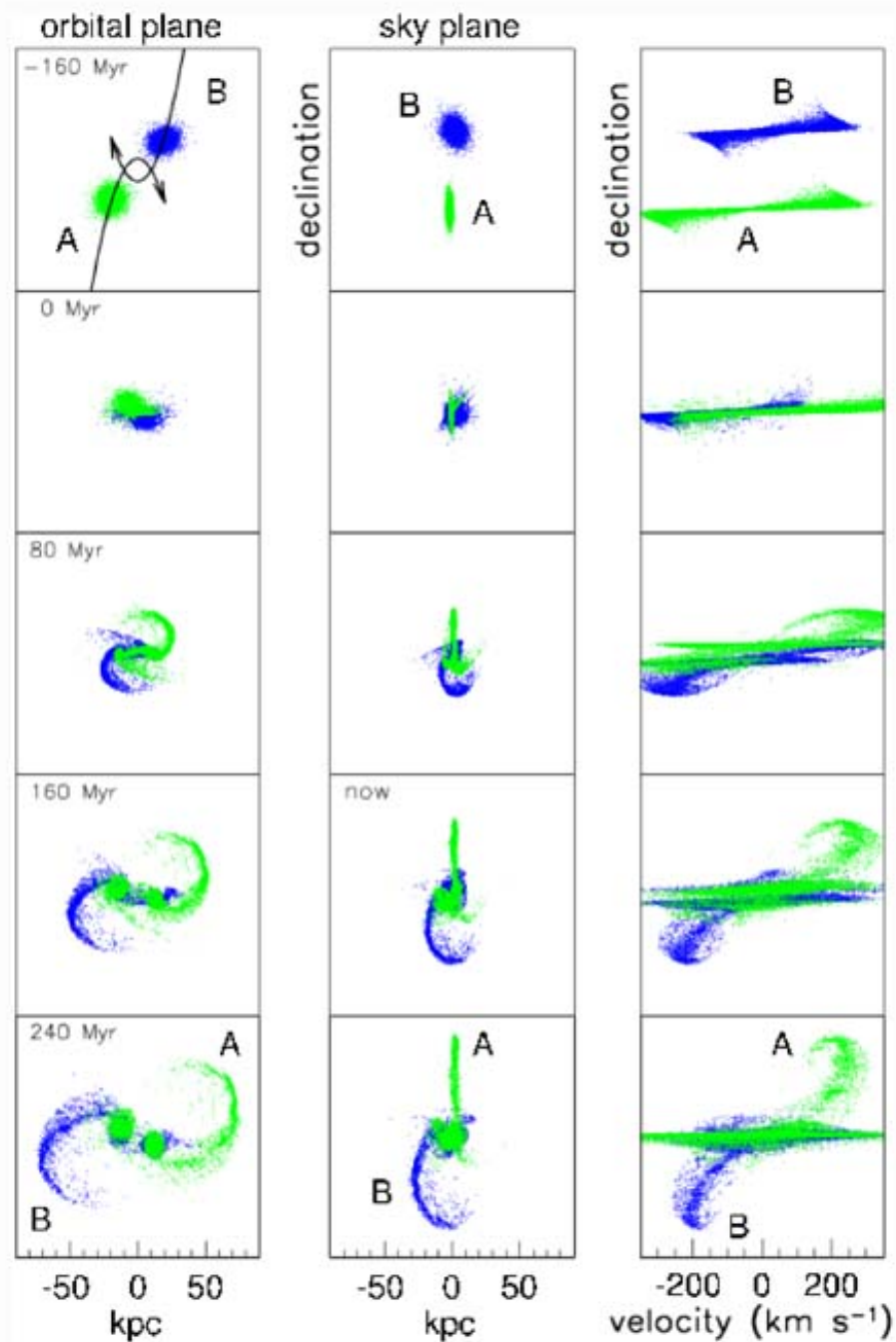
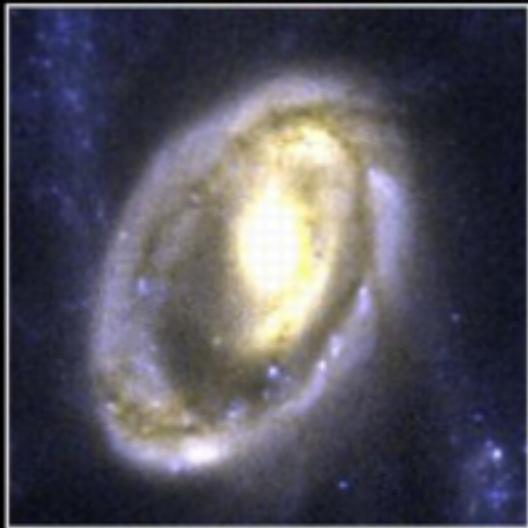
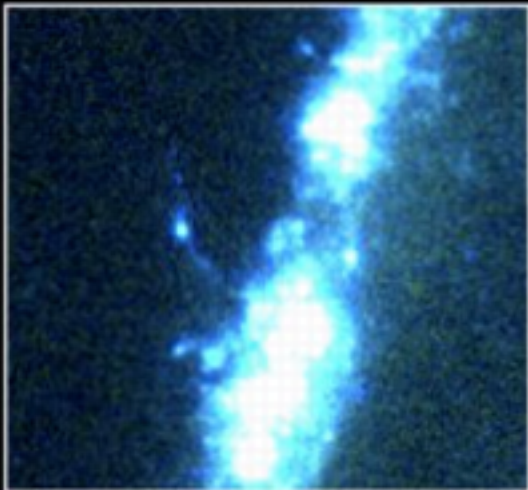


Fig 7.5 (J. Hibbard, J. Barnes) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



## Simulation of the Mice

Fig 7.6 (J. Hibbard, J. Barnes) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



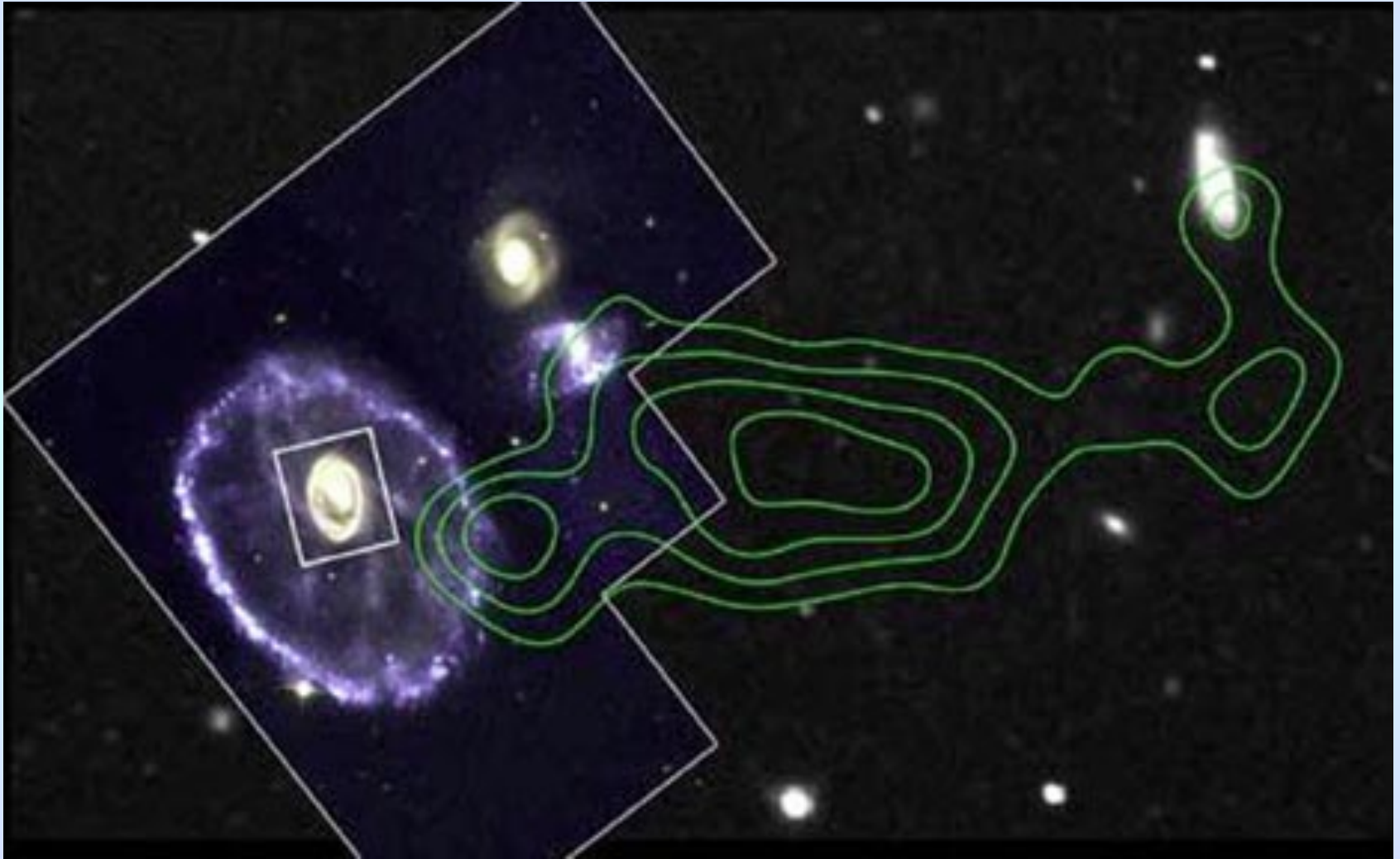
# Cartwheel Galaxy

PR95-02 • ST ScI OPO • January 1995 • K. Borne (ST ScI), NASA

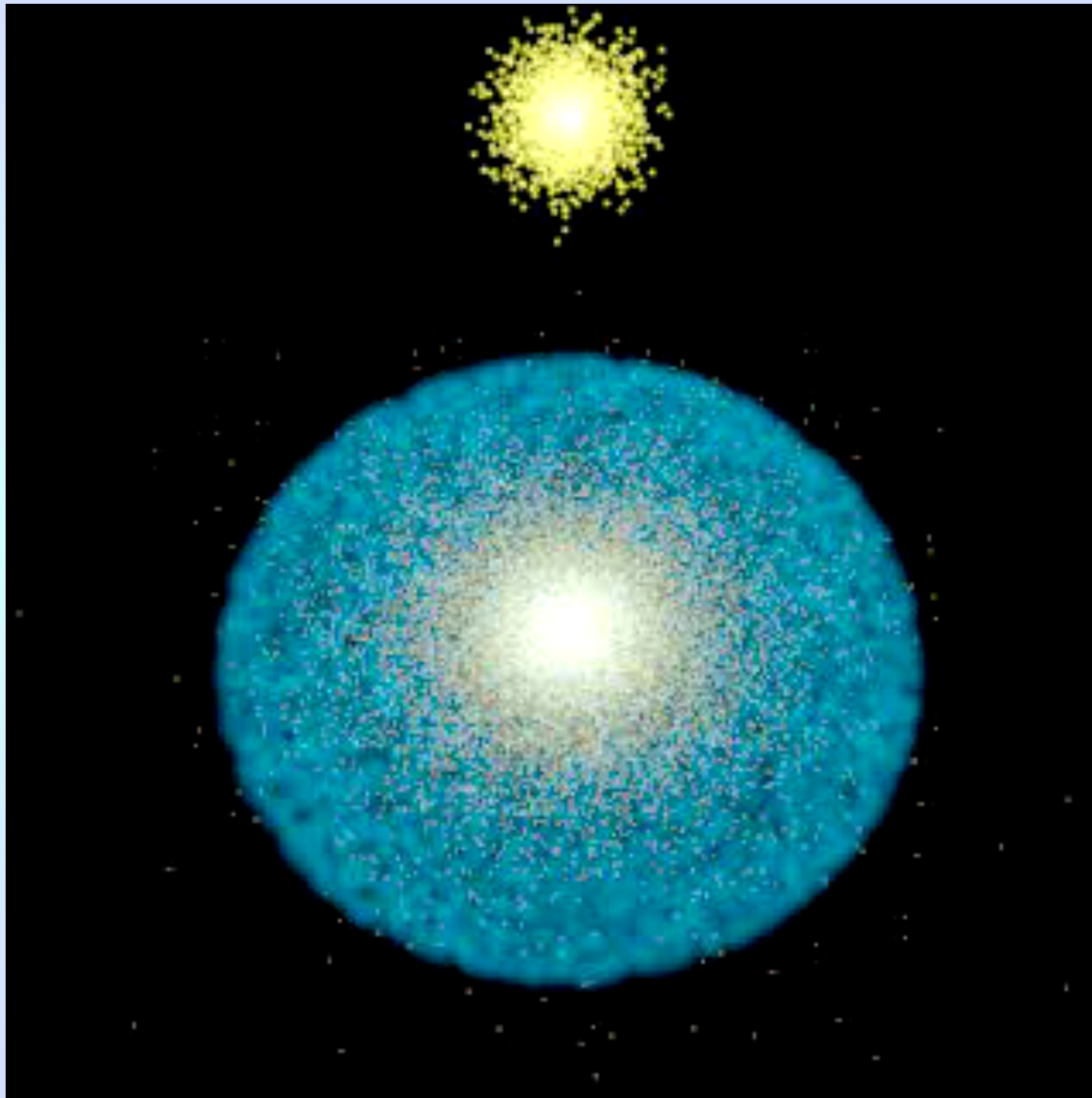
HST • WFPC2

12/23/94 zgl

# HI gas around Cartwheel



# Simulation of the Cartwheel



## Spiral Galaxy Pair NGC 3314

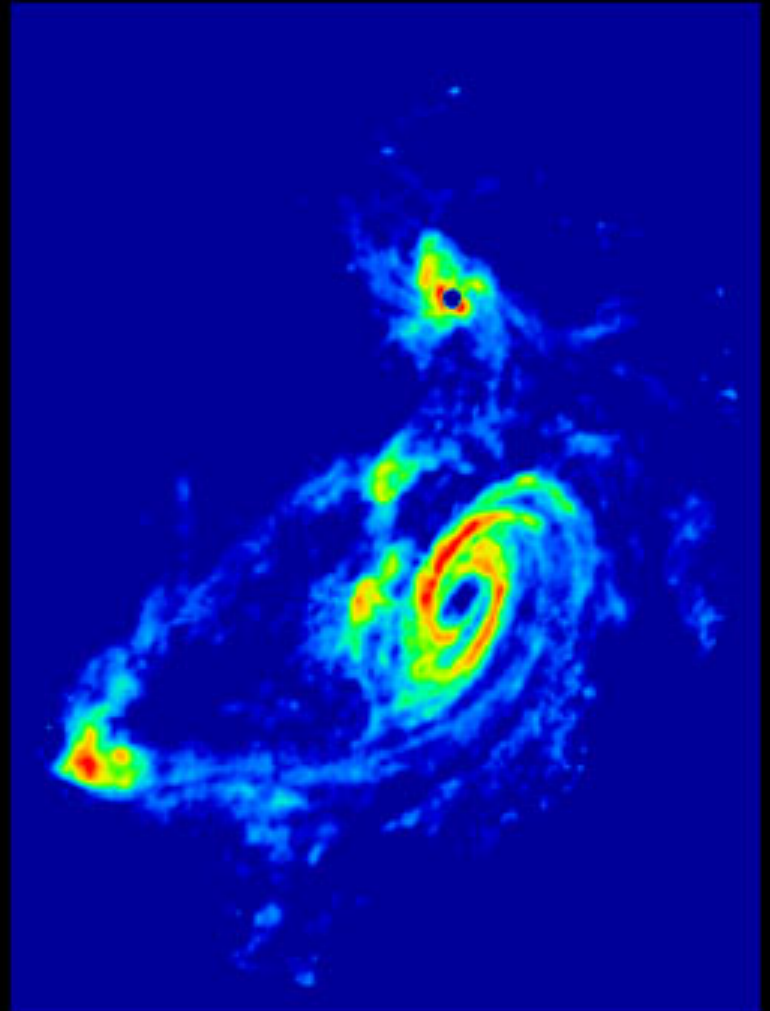
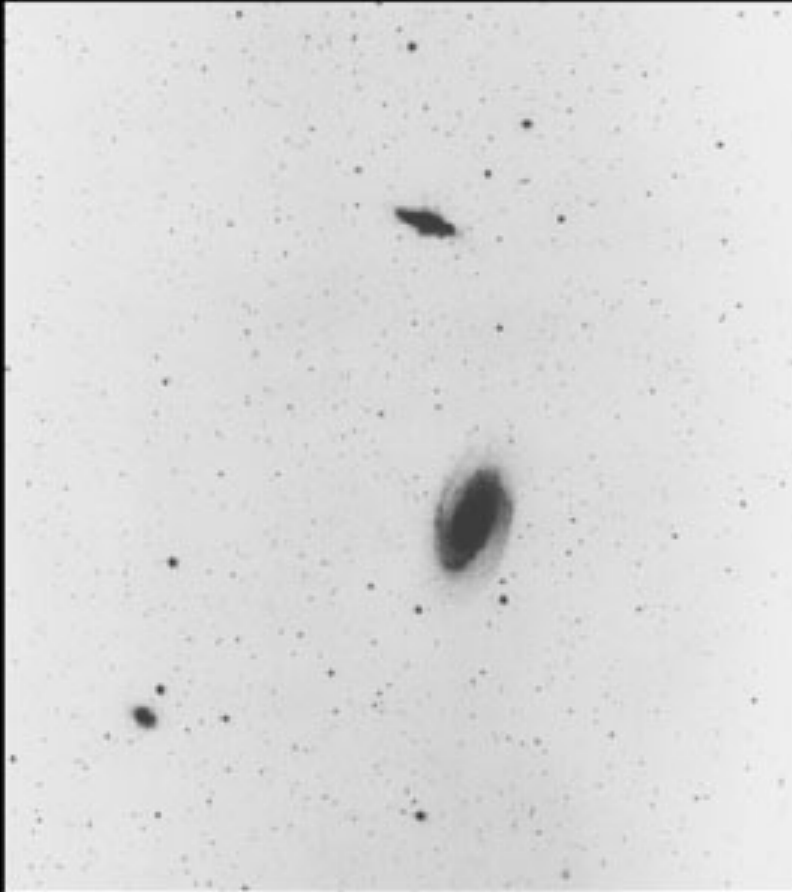


Hubble  
Heritage

# The Leo I (or M96) Group



# The M81 Group



# Compact Groups

Some groups have  $\sim 6$  large galaxies within a very small volume (with separations of only 20 to 40 kpc). Such compact systems are rare and cannot last long.



**Stephan's Quintet**

**HST • WFPC2**

NASA and S. Gallagher (Penn State University)

STScI-PRC01-22

# Stephan's Quintet in the X-ray





**Galaxy Group Seyfert's Sextet**

**HST ♦ WFPC2**

NASA, J. English (University of Manitoba)

and C. Palma (Pennsylvania State University) ♦ STScI-PRC02-22

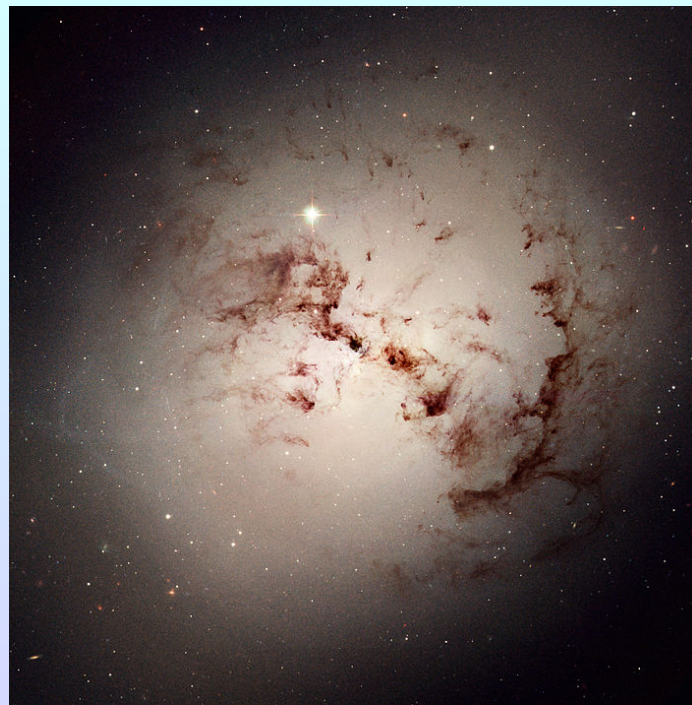
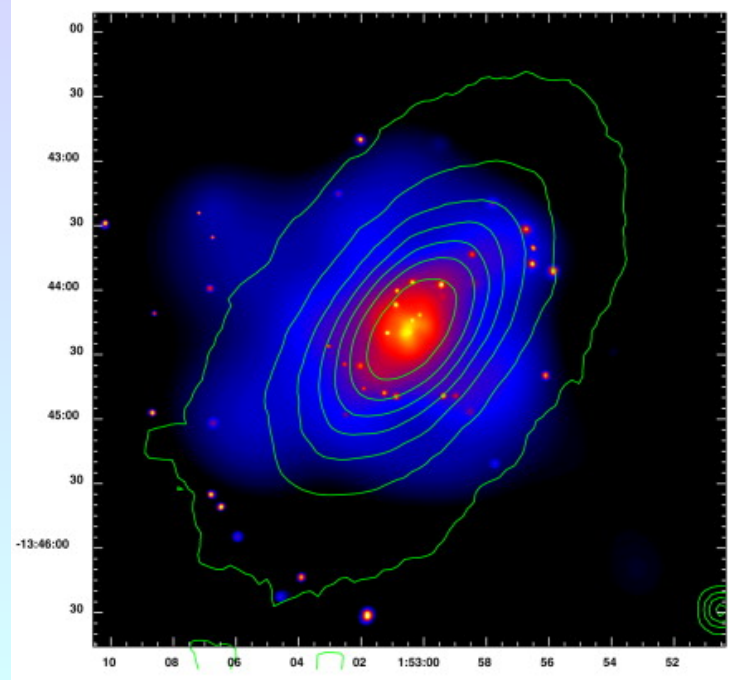
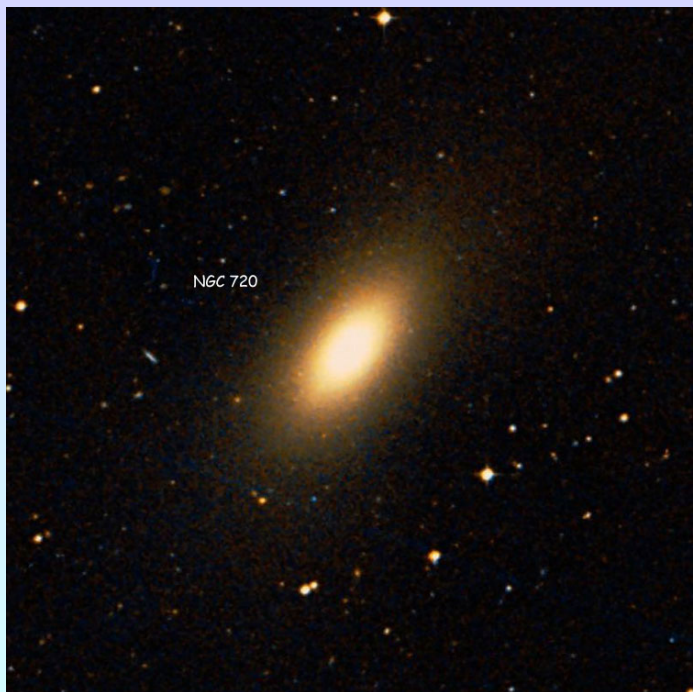
## Hickson Compact Group 87



Hubble  
Heritage

# Evolution of a Condensed Cluster





# The Milky Way and M31